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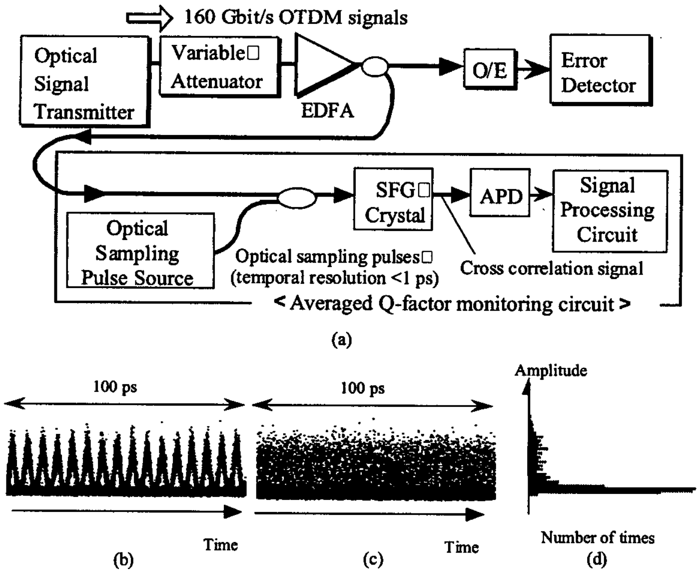

CThU3 Fig. 3. Asynchronous optical signal quality monitoring (a) Experimental setup. (b) Synchronously measured eye-diagram of 160 Gbit/s OTDM signal. (c) Asynchronously measured eye-diagram and (d) its amplitude histogram.

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CThU4 **5:45 pm**

Pattern effects and noise accumulation in concatenated all-optical regenerators

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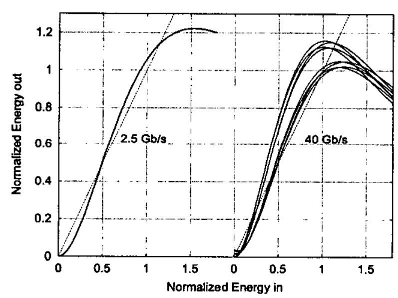
In future high-speed networks, interferometric structures based on semiconductor optical amplifiers (SOAs) are strong candidates for wavelength conversion applications and signal regeneration.[1] One of the latest reported interferometric devices is the Semiconductor Delayed-Interference Signal-wavelength Converter (DISC),[2] which allows for high-speed switching by exploiting the fast carrier-depletion related refractive index changes in the SOA.

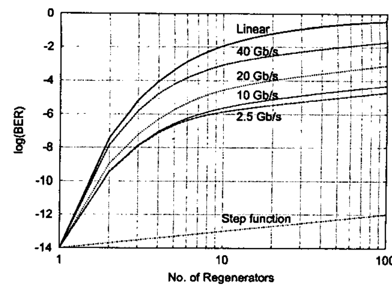
Here we use a numerical model of the DISC configuration including saturation and dynamical effects in the SOA, to generate pattern dependent transfer functions. These transfer functions are used to evaluate the noise accumulation and the BER of concatenated regenerators in a manner similar to the one proposed in,[3] but here the analysis is extended to the dynamic case, which becomes very important for bitrates > 10 *Gb/s*. The results are also valid for other interferometric based converters/regenerators.

In the numerical simulations we use a 1500 μm long SOA, the input pulse width is 5 *ps* (FWHM, RZ signal) and the signal intensity is adjusted in order to ensure a π phase-shift in the SOA. In Fig. 1 we observe the transfer characteristic of the DISC-model at two different bit-rates. The SOA is fast enough to fully recover between pulses at low bitrates. At high bitrates (> 10 *Gb/s*) the SOA no longer recovers fully between bits, causing the observed pattern dependent transfer functions.



CThU4 Fig. 1. Transfer characteristics for the DISC model. Left plot is for 2.5 *Gb/s* where no pattern effects are visible and right plot is for 40 *Gb/s* where the memory effects of the SOA are clearly visible.

The evaluation of the transfer functions are done without including noise effects. These are included in the following noise accumulation analysis, where the pattern dependent nonlinear transfer functions are approximated by "staircase" functions made by discrete sets of values $\{x_i\}$. Assuming Gaussian noise, from inline amplifiers and SOAs in the regenerators, added to the signal $s_n = x_j$ before the n'th node, we calculate a transfer probability matrix T consisting of the transfer probability elements; $t_{ij} = P(s_{n+1} = x_i \mid s_n = x_j)$. Defining a discrete probability density function (pdf) for the ZERO and ONE signal as $p_n = [P(s_n = x_1) \ . \ . \ . \ P(s_n = x_N)]^T$, we calculate the pdf at node n as $p_n = T^n \cdot p_0$.[3] The model takes full account of the noise-redistribution, leading to non-Gaussian distribution at the regenerator output.



CThU4 Fig. 2. The BER evolution of the system up to 100 concatenated repeaters. The Gaussian noise level is set to give a BER of 10^{-14} after one link. Also shown is the BER evolution with a linear- (no regeneration) and a step-function (ideal regeneration) characteristic.

In Fig. 2 we have plotted the BER as a function of the number of concatenated regenerators at different bit-rates. Pattern effects strongly influence the accumulation of noise at bitrates > 10 *Gb/s*.

The regeneration capability is significantly improved by combining two DISC devices in each node, as done with two MZIs converters in.[4] This improves the nonlinear transfer characteristics significantly and results in a reduction of the BER by two orders of magnitude, as shown in Fig. 3.

In conclusion, we have extended previous static analyses of noise-redistribution in all-optical regenerators to take dynamical effects into account and shown how pattern effects degrade the regeneration capability at high bitrates.

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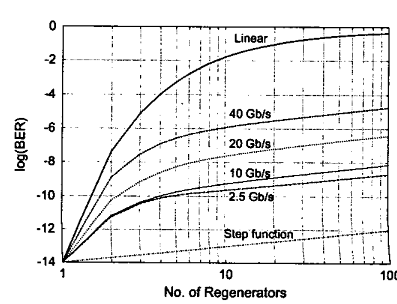

CThU4 Fig. 3. As in figure 2, but this time with two interferometers at each node. Strong improvement of the BER is observed.

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CThU5 **6:00 pm**

Multiple wavelength demultiplexing using an ultrafast nonlinear interferometer

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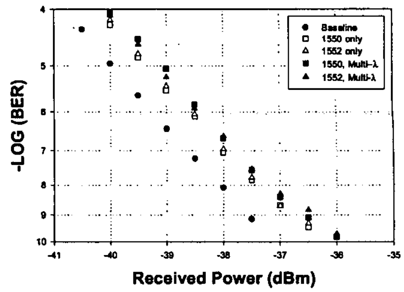
Optical rate conversion at user access nodes is a necessity in slotted optical time-division multiplexed (OTDM) networks. Various methods of rate conversion have been previously proposed. For instance, a receiver can optically buffer incoming slots and perform an all-optical rate-conversion down to electronic rates.[1] A more practical approach to rate conversion is to consider the incoming slot as N bit-interleaved OTDM channels which can each be optically demultiplexed, detected, and buffered electronically. Multiple channel demultiplexing has been previously demonstrated in a nonlinear optical loop mirror[2] and using four-wave mixing in fiber[3] and a semiconductor optical amplifier.[4] Here, we use the ultrafast nonlinear interferometer (UNI)[5] to demonstrate multiple wavelength all-optical demultiplexing.

Figure 1 shows the configuration for multiple wavelength demultiplexing using the UNI. In this setup, the aggregate OTDM data stream at a bit rate of N*10 Gbit/s is used as the control input to the UNI. We use pulse-position modulation (PPM) to eliminate patterning due to gain-saturation effects in the SOA.[6] The signal input is comprised of N optical pulse sources at 10 Gbit/s. These sources must be at N different wavelengths and their pulse widths must be less than the bit period of the aggregate OTDM data stream (100 ps/N). The N signal wavelengths are each temporally aligned with successive bit-interleaved OTDM channels on the control input. In this way, the N OTDM channels are wavelength converted to the N signal wavelengths. At the output of the UNI, the N signal channels are separated using a wavelength division multiplexer (WDM) and electronically processed at 10 Gbit/s.

Experimentally, we have demonstrated multiple wavelength demultiplexing of a 20 Gbit/s OTDM data stream using the setup shown in Figure 2. The control pulse source is a mode-locked fiber laser (MLFL) producing 2 ps pulses at 1545 nm. These pulses are pulse-position modulated (PPM) with a 10 Gbit/s pseudo-random bit pattern of length $2^{31}-1$. We optically multiplex these pulses to create a 20 Gbit/s OTDM data stream. Two additional MLFL producing 2 ps pulses at 1550 nm and 1552 nm provide the signal pulse sources. The two signal lasers are combined and temporally aligned with the control pulses using optical delay lines (ODL). At the output of the UNI, the two signal wavelengths are filtered and separated. These two outputs are then sent to a 10 Gbit/s optically preamplified receiver for bit-error-rate (BER) analysis.

Figure 3 shows the results of the bit-error rate tests for multiple wavelength operation. In each of these experiments, the individual signal powers at the input of the UNI are −5 dBm while the control power is 0 dBm. The baseline is measured using the 1545 nm output directly from the modulator. The unfilled points represent the BER performance of the switch when only a single wavelength is used for demultiplexing while the filled points show the BER performance when both signal wavelengths are used for simultaneous demultiplexing. The maximum observed power penalty for a BER of 10^{-9} was 1.5 dB.

In conclusion, we have demonstrated multiple wavelength demultiplexing of a 20 Gbit/s pulse-position modulated data stream. The interferometric SOA-based switch design requires less



CThU5 Fig. 3. Bit-error rate test results on demultiplexed UNI output.

control pulse power and has less latency than previous work making it an ideal solution for rate conversion in an OTDM receiver. Previous switching results suggest that this technique should readily scale to OTDM data rates of 80 Gbit/s, or more.[7]

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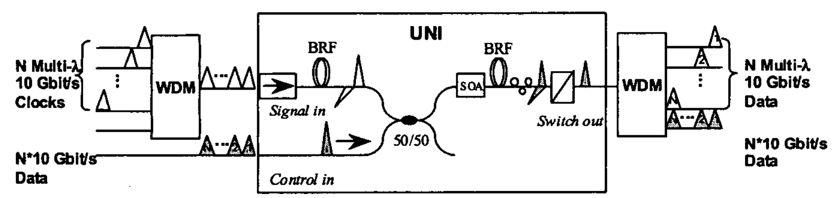
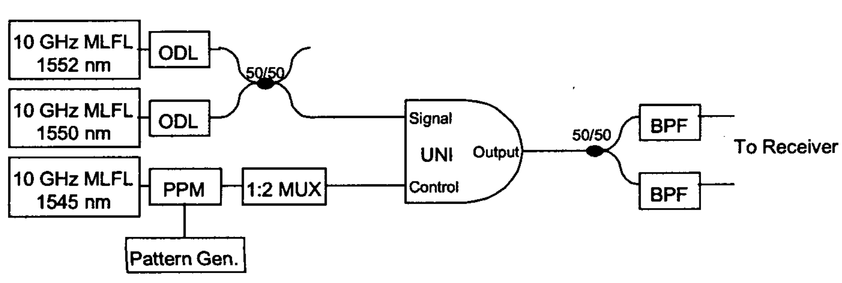


CThU5 Fig. 1. Multiple wavelength demultiplexing with an ultrafast nonlinear interferometer (UNI).



CThU5 Fig. 2. Experimental setup.

CThV **4:45 pm–6:30 pm**
Room 321/323

Novel Techniques

Norman Hodgson, *Spectra Physics Lasers, USA,* *Presider*

CThV1 **4:45 pm**

A novel technique for compensation of birefringence in active elements of solid-state lasers

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Heating of active elements (AE) of solid-state lasers gives rise to a thermal lens and birefringence. The problem of how to compensate for the birefringence in AE has been studied for many years and continues to be a subject of investigation at present. Various designs were sug-